

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
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1. REPORT DATE (DD-MM-YYYY) 01-03-2012		2. REPORT TYPE Final Report			3. DATES COVERED (From - To) 01-03-2009 to 29-02-2012	
4. TITLE AND SUBTITLE Exploration of an Opportunistic Overlaid Paradigm for Complex Networks via Stochastic Geometry				5a. CONTRACT NUMBER FA9550-09-1-0107		
				5b. GRANT NUMBER FA9550-09-1-0107		
				5c. PROGRAM ELEMENT NUMBER		
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				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Dept. of Electrical and Computer Engineering Texas A&M University College Station, TX, 77845					8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Science and Research 875 Randolph Street Suite 325 Room 3112 Arlington, VA 22203					10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-OSR-VA-TR-2012-0353	
12. DISTRIBUTION/AVAILABILITY STATEMENT Dist A.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT In this project, we focused on large complex networks and mainly investigated the following major issues: 1) We studied the overlaid complex networking systems where a primary network tier is coexisting with an opportunistic network tier. With stochastic geometry tools, we first showed that both tiers could achieve the same throughput scaling and then showed that the primary throughput scaling can be improved by allowing the opportunistic tier to help with relaying primary traffic. 2) We then studied the enabling techniques for primary vs. opportunistic coexisting network systems, where we mainly investigated how the opportunistic network senses the primary spectrum usage and detect primary occupancy in a distributed fashion, for which we established the respective asymptotic convergence results based on the Random Dynamic System theories. 3) We finally studied the related resource allocation strategies in large random networks, where we redefine the related transmission capacity concepts to quantify the system performance.						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Shuguang Cui	
U	U	U	UU		19b. TELEPHONE NUMBER (Include area code) 9798627957	

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**To:** technicalreports@afosr.af.mil

**Subject:** Final Report to Dr. Robert Bonneau

**Contract/Grant Title:** Exploration of an Opportunistic Overlaid Paradigm for Complex Networks via Stochastic Geometry

**Contract/Grant #:** FA9550-09-1-0107

**Reporting Period:** March 1, 2009 to Feb. 28, 2012

**Annual accomplishments:** In the past three years, we have been mainly investigating the following problems: 1) We studied the transmission capacities of two coexisting asymptotically large single-hop wireless networks (a primary network vs. a secondary network) that operate in the same geographic region and share the same spectrum, where the primary (PR) network has a higher priority to access the spectrum without particular considerations for the secondary (SR) network, and the SR network limits its interference to the PR network by carefully controlling the density of its transmitters. By applying the stochastic geometry theory, the stable distribution theory, and the asymptotic analysis, we derive the transmission capacities for both of the two networks and quantify their tradeoffs; 2) We studied the scaling laws for the throughputs and delays of two coexisting asymptotically large multihop wireless networks, still a primary network vs. a secondary network. We first show that both networks can achieve the same throughput scaling law as for a stand-alone wireless network if proper transmission schemes are deployed. By using a fluid model, we also show that both networks can achieve the same delay-throughput tradeoff as the optimal one established earlier for a stand-alone wireless network; 3) We studied the asymptotic scaling laws for throughput and delay in a supportive overlaid system, where the secondary network coexists with a primary network to share the same resources of time, space, and frequency. In particular, we considered the case where the secondary network is willing to help relaying the information for the primary network. With such opportunistic help, we showed that the secondary network can improve the primary network performance while maintaining a nontrivial secondary performance; 4) We investigated the asymptotic performance of random access schemes with cognitive spectrum sensing in a complex overlaid system with both primary users and secondary users. We first studied the throughput scaling for both the primary and secondary users; and then proposed a new metric, the *asymptotic multiplexing gain*, to fully quantify the fundamental performance tradeoff between the primary and the secondary networks; 5) We studied how to estimate the primary spectrum usage in a distributed fashion over multiple opportunistic nodes. In particular, we model the primary spectrum occupancy state as an evolving linear dynamic system, where multiple opportunistic nodes each runs a Kalman filter to estimate the state vector sequence. By allowing communication among those nodes, we proved that the distributed estimation error will asymptotically converge to a fixed distribution; 6) We studied the binary distributed detection problem, where multiple opportunistic nodes collaborate to detect the existence of primary users over a certain band. By allowing certain message passing routines among neighboring nodes and applying a mixed-time-scale local updating rule, we proved that both the miss-detection probability and the false-alarm probability converge to zeros at each distributed node; 7) We studied the problem of discrete power control in a random but clustered wireless ad hoc network, where the transmitters are allocated according to a stationary homogeneous Poisson point process. By applying the analysis with stochastic geometry, we quantified the network performance in terms of the redefined transmission capacity.

### Archival publications during reporting period: :

1. C. Yin, L. Gao, T. Liu, and S. Cui, "Transmission capacities for overlaid wireless ad hoc networks with outage constraints," Proceedings of ICC, Dresden, Germany, June, 2009.
2. L. Gao, R. Zhang, C. Yin, and S. Cui, "Delay-Throughput Tradeoff for Supportive Two-Tier Networks," Proceedings of ISIT, Seoul, South Korea, July 2009.
3. C. Yin, T. Liu, and S. Cui, "Generalized Results of Transmission Capacities for Overlaid Wireless Networks," Proceedings of ISIT, Seoul, South Korea, July 2009.
4. C. Yin, L. Gao, and S. Cui, "Delay-Throughput Tradeoff for Overlaid Wireless Networks of Different Priorities," Proceedings of ISIT, Seoul, South Korea, July 2009.
5. C. Yin, C. Chen, and S. Cui, "Stable Distribution Based Analysis of Transmission Capacities for Overlaid Wireless Networks," Proceedings of WCSP, Nanjing, China, Nov. 2009.
6. R. Zhang, Y.-C. Liang, and S. Cui, "Dynamic Resource Allocation in Cognitive Radio Networks: A Convex Optimization Perspective," *IEEE Signal Processing Magazine* special issue on Convex Optimization on Signal Processing, Vol. 27, No. 3, pp. 102-114, May 2010.
7. C. Yin, L. Gao, and S. Cui, "Scaling Laws of Overlaid Wireless Networks: A Cognitive Radio Network vs. A Primary Network," *IEEE/ACM Transactions on Networking*, Vol. 18, No. 4, pp. 1317-1329, Aug., 2010.
8. L. Zhang, R. Zhang, Y.-C. Liang, Y. Xin, and S. Cui, "On the Relationship Between the Multi-antenna Secrecy Communications and Cognitive Radio Communications," *IEEE Transactions on Communications*, Vol. 58, No. 6, pp. 1877-1886, June 2010.
9. A. Banaei, C. N. Georgiades, and S. Cui, "Asymptotic Performance of ALOHA-Based Cognitive Overlaid Networks," *Proceedings: the IEEE SECON workshop on Networking Technologies for Software Defined Radio and White Space*, 5 pages, Boston, June, 2010.
10. Q. Zhou, L. Gao, R. Liu, and S. Cui, "Connectivity of Two-Tier Networks," *Proceedings: IEEE GLOBECOM Workshop on Complex and Communication Networks (CCNet 2010)*, 5 pages, Miami, Dec., 2010.
11. D. Li, C. Yin, C. Chen, and S. Cui, "A Selection Region Based Routing Protocol for Random Mobile ad hoc Networks," *Proceedings: IEEE GLOBECOM Workshop on Heterogeneous, Multi-hop Wireless and Mobile Networks (HeterWMN)*, 5 pages, Miami, Dec., 2010.
12. C. Huang, J. Jiang, and S. Cui, "Asymptotic Capacity of Large Fading Relay Networks with Random Node Failures," *IEEE Transactions on Communications*, Vol. 59, No. 8, pp. 2306-2315, August 2011.
13. L. Gao, R. Zhang, C. Yin, and S. Cui, "Throughput and Delay Scaling in Supportive Two-Tier Networks," *IEEE Journals on Selected Areas of Communications* special issue on Cooperative Networking Challenges and Applications, 2011. (To appear)

14. M. Zeng, R. Zhang, and S. Cui, "On Design of Distributed Beamforming for Two-Way Relay Networks," *IEEE Transactions on Signal Processing*, Vol. 59, No. 5, pp. 2284-2295, May 2011.
15. S. Kar, S. Cui, H. V. Poor, and J. Moura, "Convergence Results in Distributed Kalman Filtering," *Proceedings: IEEE ICASSP*, Prague, May, 2011.
16. S. Kar, R. Tandon, H. V. Poor, and S. Cui, "Distributed Detection in Noisy Sensor Networks," *Proceedings: IEEE ISIT*, St. Petersburg, Russia, August, 2011.
17. Q. Zhou, S. Kar, L. Huie, H. V. Poor, and S. Cui, Robust Distributed Least-Squares Estimation in Sensor Networks with Node Failures, *Proceedings: IEEE GLOBECOM*, Houston, December, 2011.
18. S. Kar, H. V. Poor, and S. Cui, Bandit Problems in Networks: Asymptotically Efficient Distributed Allocation Rules, *Proceedings: 50th IEEE Conference on Decision and Control and European Control Conference (CDC/ECC)*, Orlando, FL, December, 2011.
19. Q. Zhou, S. Kar, L. Huie, and S. Cui, Distributed Estimation in Sensor Networks with Imperfect Model Information: An Adaptive Learning-Based Approach, to appear at *IEEE ICASSP*, Kyoto, Japan, March 2012.
20. C. Huang, J. Jiang, and S. Cui, "Asymptotic Capacity of Large Relay Networks with Conferencing Links," *IEEE Transactions on Communications*, 2011. (To appear)
21. A. Banaei, C. N. Georghiades, and S. Cui, "Study of Large Overlaid Cognitive Radio Networks: From Throughput Scaling to Asymptotic Multiplexing Gain," 2012. (Under revision)

**Changes in research objectives, if any:** None

**Change in AFOSR program manager, if any:** None

**Extensions granted or milestones slipped, if any:** None

**Include any new discoveries, inventions, or patent disclosures:**

- **Stable Distribution Based Analysis of Transmission Capacities for Overlaid Wireless Networks.** In this work we study the transmission capacities of two coexisting asymptotically large wireless networks (a primary network vs. a secondary network) that operate in the same geographic region and share the same spectrum, where the primary (PR) network has a higher priority to access the spectrum without particular considerations for the secondary (SR) network, and the SR network limits its interference to the PR network by carefully controlling the density of its transmitters. Considering a general deterministic power-law channel model with a path-loss exponent  $\alpha > 2$  and a constant transmission power, by applying the stable distribution theory and asymptotic analysis, we derive the transmission capacities for both of the two networks and quantify their tradeoff. Numerical results show that if the PR network permits a small increase of its outage probability, the sum transmission capacity across the two networks (i.e., the overall spectrum efficiency per unit area) could be boosted significantly over that of a single network, which generalizes all the existing results. We also find that Rayleigh fading can

enhance the transmission capacity gain of the overlaid networks over that of a stand-alone PR network.

- Scaling Laws for Overlaid Wireless Networks: A Cognitive Radio Network vs. a Primary Network.** In this work we study the scaling laws for the throughputs and delays of two co-existing asymptotically large multihop wireless networks that operate in the same geographic region. The primary network consists of Poisson distributed legacy users of density  $n$ , and the secondary network consists of Poisson distributed cognitive users of density  $m$ , with  $m > n$ . The primary users have a higher priority to access the spectrum without particular considerations for the secondary users, while the secondary users have to act conservatively in order to limit the interference to the primary users. With a practical assumption that the secondary users only know the locations of the primary transmitters (not the primary receivers), we first show that both networks can achieve the same throughput scaling law as what Gupta and Kumar established for a stand-alone wireless network if proper transmission schemes are deployed, where a certain throughput is achievable for each individual secondary user (i.e., zero outage) with high probability. By using a fluid model, we also show that both networks can achieve the same delay-throughput tradeoff as the optimal one established by El Gamal for a stand-alone wireless network.
- Asymptotic Performance of Supportive Overlaid Wireless Networks.** Consider a wireless network that has two tiers with different priorities: a primary tier vs. a secondary tier, which is an emerging network scenario with the advancement of cognitive radio technologies. The primary tier consists of randomly distributed legacy nodes of density  $n$ , which have an absolute priority to access the spectrum. The secondary tier consists of randomly distributed cognitive nodes of density  $m = n^\beta$  with  $\beta \geq 2$ , which can only access the spectrum opportunistically to limit the interference to the primary tier. Based on the assumption that the secondary tier is allowed to route the packets for the primary tier, we investigate the throughput and delay scaling laws of the two tiers in the following two scenarios: i) the primary and secondary nodes are all static; ii) the primary nodes are static while the secondary nodes are mobile. With the proposed protocols for the two tiers, we show that the primary tier can achieve a per-node throughput scaling of  $\lambda_p(n) = \Theta(1/\log n)$  in the above two scenarios. In the associated delay analysis for the first scenario, we show that the primary tier can achieve a delay scaling of  $D_p(n) = \Theta(\sqrt{n^\beta \log n \lambda_p(n)})$  with  $\lambda_p(n) = O(1/\log n)$ . In the second scenario, with two mobility models considered for the secondary nodes: an i.i.d. mobility model and a random walk model, we show that the primary tier can achieve delay scaling laws of  $\Theta(1)$  and  $\Theta(1/S)$ , respectively, where  $S$  is the random walk step size. The throughput and delay scaling laws for the secondary tier are also established, which are the same as those for a stand-alone network.
- Large Overlaid Cognitive Radio Networks: From Throughput Scaling to Asymptotic Multiplexing Gain.** In this work we study the asymptotic performance of two overlaid wireless ad-hoc networks that utilize the same temporal, spectral, and spatial resources based on random access schemes. The primary network consists of Poisson distributed legacy users with density  $n$  and the secondary network consists of Poisson distributed cognitive radio users with density  $m = n^\beta$  ( $\beta > 0, \beta \neq 1$ ) that utilize the spectrum opportunistically. Both networks are *decentralized* and deploy ALOHA protocols where the secondary nodes are equipped with range-limited *perfect* spectrum sensors to monitor and protect primary transmissions. We study

the problem in two distinct regimes, namely  $\beta > 1$  and  $0 < \beta < 1$ . We show that in both cases, the two networks can achieve their corresponding stand-alone throughput scaling even without secondary spectrum sensing (i.e., sensing range set to zero), which implies the need for a more comprehensive performance metric than just throughput scaling to evaluate the influence of the overlaid interactions. We thus introduce a new criterion, termed as the *asymptotic multiplexing gain*, which captures the effect of spectrum sensing and inter-network interferences. Furthermore, based on this metric we demonstrate that spectrum sensing can substantially improve the network performance when  $\beta > 1$ . On the contrary, spectrum sensing turns out to be unnecessary when  $\beta < 1$ .

- Distributed Estimation of the Primary Spectrum Usage.** In this work, we study the distributed estimation problem in a complex network, where each networked node converges to the same intelligence just based on local observations and information exchanges with its neighbors. In particular, we estimate the state of a potentially unstable linear dynamical system in the framework of distributed Kalman filtering. It is shown that, in a weakly connected communication network, there exist (randomized) gossip based information dissemination schemes leading to a stochastically bounded estimation error at each node for any non-zero rate of inter-node communication. A gossip-based information exchange protocol, the M-GIKF, is presented. Under the assumption of global detectability of the signal/observation model, it is shown that the distributed M-GIKF leads to a stochastically bounded estimation error at each node. In particular, the conditional estimation error covariance sequence at each node is shown to evolve as a random Riccati equation (RRE) with Markov modulated switching, which is analyzed through a random dynamical system (RDS) formulation. The estimation error at each node is shown asymptotically converging to an invariant distribution.
- Distributed Detection of Primary User Existence.** In this work we consider distributed detection over a noisy network (over a binary hypothesis, e.g., the existence of primary users), in which each connected node pair can communicate over an additive noise channel. With non-identically distributed generic node observations, a mixed time scale recursive algorithm for binary hypothesis testing over such networks is proposed. Under some mild assumptions on network connectivity and global detectability (the positivity of the global or centralized Kullback-Liebler divergence), this algorithm yields asymptotically zero probabilities of Type-I and Type-II errors (henceforth referred to as probabilities of error). When node observations are identically distributed, a simplified single time scale version of the proposed algorithm is shown to achieve asymptotically zero probabilities of error. Convergence rate guarantees in terms of asymptotic normality of certain scaled decision variables are provided for this simplified procedure. As an example, a practical Gaussian detection network is considered, for which the error decay exponents are explicitly characterized in terms of the network and noise parameters.
- Discrete Power Control in Clustered Wireless ad hoc Network.** In this work, a new discrete power control strategy is explored in a complex clustered wireless ad hoc network. Transmitters in the network form a stationary homogeneous Poisson point process (PPP) on a 2-D plane. Each transmitter has a random number of receivers that are distributed in a cluster region with  $N$  tessellated layers. There are  $N$  level transmit powers used by each transmitter and which level of power is used depends on which layer the desired receiver is located in a cluster. The outage probabilities for receivers at different layers are derived. The optimal control scheme to

maximize the contention intensity, which is used to calculate the redefined transmission capacity (TC) in our setting, is found. The proposed power control has the effect of balancing the spatial throughput achieved by receivers at all distance layers such that throughput fairness among receivers is achieved. Simulation results show that the proposed discrete power control strategy significantly improves TC and outperforms other previous power control strategies in a PPP network.

- No inventions and patent disclosures.